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O. Guilbaud,[1,*] F. Tissandier,[2] J-P. Goddet,[2] M. Ribière,[2] S. Sebban,[2] J. Gautier,[2] D. Joyeux,[3] D. Ros,[1] K. Cassou,[1,5] S. Kazamias,[1] A. Klisnick,[1] J. Habib,[2] P. Zeitoun,[2] D. Benredjem,[4] T. Mocek,[6] J. Nedjl,[6] S. de Rossi,[3] G. Maynard,[5] B. Cros,[5] A. Boudaa,[5] and A. Calisti[7]

[1]*LIXAM, CNRS, Univ Paris-Sud, bat 350 campus d'Orsay, 91405 Orsay, France*
[2]*LOA, ENSTA-Ecole Polytechnique, Chemin de la Hunière, 91761 Palaiseau, France*
[3]*LCFIO, CNRS, Univ Paris-Sud, 91127 Palaiseau, France*
[4]*LAC, CNRS, Univ Paris-Sud, bat 503 campus d'Orsay, 91405 Orsay, France*
[5]*LPGP, CNRS, Univ Paris-Sud, bat 210 campus d'Orsay, 91405 Orsay, France*
[6]*PALS, Institute of Physics, Academy of Sciences of the Czech Republic, 182 21 Prague 8, Czech Republic*
[7]*PIIM, Univ de Provence, 13397 Marseille, France*
**Corresponding author: olivier.guilbaud@u-psud.fr*

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We present what we believe to be the first measurement of the spectral properties of a soft x-ray laser seeded by a high-order harmonic beam. Using an interferometric method, the spectral profile of a seeded Ni-like krypton soft x-ray laser (32.8 nm) generated by optical field ionization has been experimentally determined, and the shortest possible pulse duration has been deduced. The source exhibits a Voigt spectral profile with an FWHM of 3.1 ± 0.3 mÅ, leading to a Fourier-transform pulse duration of 4.7 ps. This value is comparable with the upper limit of the soft x-ray pulse duration determined by experimentally investigating the gain dynamics, from which we conclude that the source has reached the Fourier limit. The measured bandwidth is in good agreement with the predictions of a radiative transfer code, including gain line narrowing and saturation rebroadening. © 2010 Optical Society of America

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Important progress has been achieved in laser-produced soft x-ray coherent beams, opening the way to compact and high-repetition-rate devices. One promising approach is the seeding of plasma-based soft x-ray lasers (SXRLs) with a fully coherent, femtosecond high-order harmonic (HOH) of an IR laser [1–3]. When a soft x-ray laser amplifier is correctly seeded by HOH radiation, the output emission is more energetic than HOH, highly collimated, and spatially coherent [3] with a pulse duration in the picosecond range [4]. In this Letter we show experimentally that a seeded soft x-ray laser pulse is temporally fully coherent and its duration reaches the Fourier-limit, the smallest pulse duration allowed by its bandwidth. The temporal coherence and the gain dynamics of a seeded soft x-ray laser emitting at 32.8 nm have been measured. From these results, the spectral profile and information on the pulse envelope duration have been obtained and compared. Numerical work has been undertaken to simulate the lineshape and shows a good agreement with the bandwidth value found experimentally.

The seeded SXRL was generated with an experimental configuration similar to the one described in [2]. We used a 10 Hz multiterawatt Ti:sapphire laser system that provides two independent 34 fs laser pulses at a central wavelength of 815 nm. The first laser beam, carrying an energy of 10 mJ, was focused in a 7-mm-long gas cell filled with 30 mbar of argon in order to generate the HOH seed beam. A grazing incidence toroidal mirror was imaging the output of the HOH source with a magnification of 1.5 at the entrance of the x-ray laser plasma amplifier. This amplifier is an optical field ionization (OFI) x-ray laser generated by the second IR laser beam that delivers an ~600 mJ pulse, circularly polarized, on a gas target filled with krypton. A lasing gain at 32.8 nm is obtained on the $3d^9 4d(^1S_0) \rightarrow 3d^9 4p(^1P_1)$ transition of Ni-like krypton ion at 32.8 nm [5]. The wavelengths of the 25th harmonic and of the amplifier are monitored with a transmission grating spectrometer and precisely matched by tuning the chirp of the IR laser pulse generating the harmonics. The SXRL beam is monitored by detecting the extreme-UV (XUV) beam far-field image with an XUV CCD camera placed after a multilayer mirror. When no seed beam is injected, a strongly divergent beam (15 mrad) is emitted by the plasma resulting from the amplification of the amplifier spontaneous emission (ASE). When a HOH seed is properly injected, the SXRL beam appears above this pattern, presenting a small divergence ($\leq$ mrad). A seeding amplification factor α is calculated by taking the energy of the SXRL beam divided by the HOH seed beam energy. The most effective configuration in terms of amplification was found for a 30 mbar pressure and a amplifier length of $L = 6$ mm.

The amplification factor has been measured as a function of the delay between the plasma creation and the seed beam injection [6]. The results are presented in Fig. 1. Starting from a negligible value for a null delay, α reaches a maximum for a seed beam arriving in the gas cell 3 ps after the IR beam generating the plasma. When adding more delay, α decreases to reach again a negligible value. For a delay of 8 ps, α is 10% of the peak value when corrected from the ASE level. This means that the laser gain in the plasma amplifier lasts in total 8 ps after the plasma creation or 5 ps after the amplification peak. The final amplified pulse will have a temporal envelope starting from the HOH pulse and growing after it as

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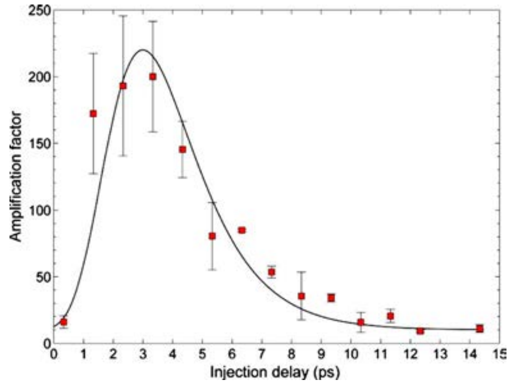

Fig. 1. (Color online) Amplification factor α as a function of the delay between the IR pulse creating the plasma and the HOH pulse in the amplifier stage. Each point represents an average on different SXRL shots, and the error bar represents the standard deviations. The black curve is shown to guide the eye.

a wake [4,7]. Its temporal extension will be limited by the plasma gain duration. According to the results presented above, for an injection time of 3 ps, the upper limit of the pulse duration is hence $\tau_{max}=5$ ps.

For this optimal delay value, the spectral bandwidth of the emitted radiation has been measured. Owing to its extremely narrow linewidth the spectral profile cannot be resolved by the spectrometer. We used instead an interferometric method. The seeded laser beam has been directed toward a variable path difference interferometer represented in Fig. 2 [8]. The fringes produced by the interferometer are recorded on an XUV CCD. A path difference between the two interfering beamlets can be introduced without moving laterally them, ensuring that a fringe visibility decrease is not due to a loss in spatial coherence. The spectral profile of the incoming radiation can be reconstructed through a Fourier transform of the fringe visibility evolution with path difference.

This evolution is presented in Fig. 3. Each point is an average of five consecutive shots, and the error bar stands for the standard deviation. The experimental data were accurately fitted with the product of a decreasing exponential function and a Gaussian function (dotted curve). The coherence time τ_c, defined as the path difference that decreases the maximum visibility by a factor $1/e$, was inferred as $\tau_c=5.5\pm0.3$ ps. The fitted evolution of the visibility corresponds to a laser line with a Voigt spectral profile and a linewidth of $\Delta\nu=(8.7\pm0.7)10^{10}$ Hz or $\Delta\lambda=3.1\pm0.3\pm$ mÅ as shown in the inset of Fig. 3.

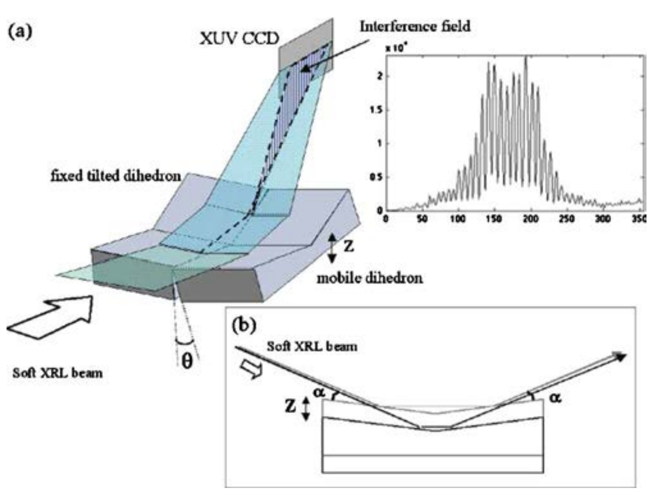

Fig. 2. (Color online) Principle of the variable path difference interferometer. (a) General view of the two dihedrons. The hatched area represents the interference field. (b) Side view of the interferometer when a dihedron is vertically moved.

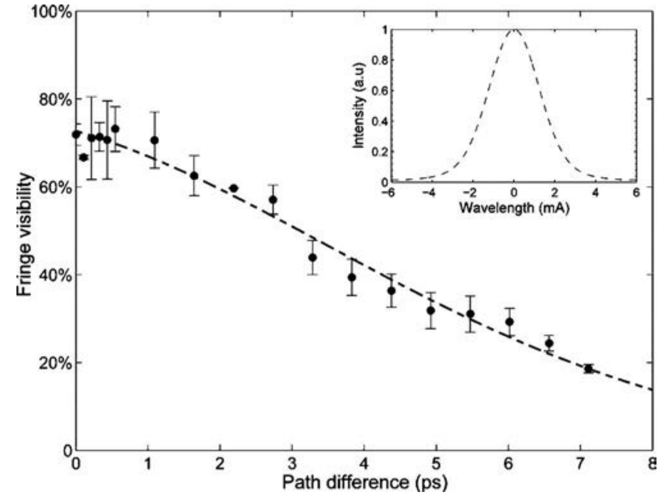

Fig. 3. Interference fringes visibility as a function of the path difference for the optimal amplification conditions (see text). The dotted curve represents the result of an exponential Gaussian fitting. Inset, SXRL line reconstructed spectrum.

The coherence time is close to the upper limit τ_{max} of the pulse duration obtained above, demonstrating that the SXRL pulse is fully temporally coherent. More accurately, we deduced from the reconstructed spectrum that the Fourier-limited intensity envelope would have a temporal width (at half-maximum) of $\tau_{min}=4.7$ ps, which is the smallest duration the SXRL pulse can reach. This minimum value is very close to the upper limit of the pulse duration $\tau_{max}=5$ ps. The real pulse duration must be between these two values and is, in conclusion, close to the Fourier limit $\tau_{\min}$.

The experimental linewidth was first compared with a simple numerical modeling. The spectral shape of the HOH seed is estimated from the grating spectrometer data. The bandwidth of the x-ray laser amplifier results first from the homogeneous broadening of the plasma line. An FWHM of $\Delta\lambda_L=5$ mÅ has been calculated with a collisional-radiative model that takes into account the non-Maxwellian nature of the electron energy distribution [9]. An inhomogeneous contribution has also been introduced. Simulations with the PPP [10] code show that the ion Stark effect can be neglected. However, a rapid ion heating is following the ionization by the IR laser optical field, because the OFI plasma is produced in a state where important ion correlations exist [11]. The plasma relaxes rapidly in an uncorrelated form after a characteristic time equal to the inverse of the plasma frequency (a few hundreds of femtoseconds). For the amplifier density conditions the ion temperature reached after this relaxation is $T_i=6$ eV, leading to a Doppler broadening FWHM $\Delta\lambda_D = 7$ mÅ. The evolution of the line profile as a function of the amplification length L has been finally calculated [12] in order to take into account gain narrowing and possible saturation rebroadening. The energy of the HOH seed has been set to obtain an amplification factor of 200 for an amplification length $L = 6$ mm, equal to the experimental value. Initial spontaneous emission has been neglected. For $L = 6$ mm, an SXRL linewidth (FWHM) of $\Delta\lambda = 3.25$ mÅ is found, which is in good agreement with the experiment.

A more rigorous treatment of the amplification using a Bloch–Maxwell description predicts an XUV pulse shape composed of three parts: a long low-level ASE pedestal, a short intense transient phase of Rabi oscillations, and a long coherent decay trail [13,14]. Our theoretical approach can describe precisely the coherent decay part of the pulse but not the transient phase. This part would lead in Fig. 3 to rapid modulations of the fringe visibility for small path differences. A quantitative estimation based on pulse temporal profiles similar to those calculated by [13] shows that, in the best case, only the first visibility oscillation would be distinguishable from the experimental shot-to-shot fluctuations.

We present in this Letter the first (to our knowledge) demonstration of a fully longitudinally coherent soft x-ray laser beam using the seeding scheme. The spectral profile of a 32.8 nm Ni-like krypton OFI-seeded soft x-ray laser has spectral width of 3.1 ± 0.3 mÅ. The corresponding Fourier-limited pulse duration (4.7 ps) closely matches the experimental measurement of the amplifier gain lifetime that follows this seed injection time. This fact demonstrates that in the spectro-temporal domain this soft x-ray laser source has reached the Fourier limit. Besides, the spectral width has been compared with numerical simulations, including a nonnegligible Doppler inhomogeneous broadening arising from a rapid heating of the ion (up to 6 eV) of the initially correlated OFI plasma. The calculated line width is in good agreement with our experimental measurement. More refined details on the line profile, such as sidebands due to Rabi oscillations, should be visible with this technique by taking smaller path difference steps, but such an experiment requires a very stable source.

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